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A Conjugate Study of ULF Waves at the Cusp

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Abstract

This report summarizes a three year study of magnetic variations measured near the footprint of the magnetospheric cusp in conjugate hemispheres. During that time data were collected from fluxgate and induction magnetometers and compared with optical data from all-sky cameras and meridian scanning photometers. The spectrum of fluctuations observed near the cusp spans a frequency range from near dc to, and above, our instrument Nyquist frequency of 50 millihertz. While the spectral power is known to diminish with frequency, there are two spectral bands which carry important information concerning the physical processes taking place along cusp field lines. In the lowest frequency band, ranging from dc to approximately 10 millihertz, are a collection of signals which show the dominant spectral power. In the central cusp there occur incoherently superposed wavelets which are observed simultaneously in both hemispheres. Our analysis, and that of our colleagues, shows these to be the resonant response of the outermost portions of the geomagnetic field near the magnetopause to the impulsive pressure variations carried by the solar wind. To the morning and evening sides of the cusp are poleward travelling pulses which appear to be line currents connecting the ionosphere with the magnetopause. We conjecture that these field aligned currents are driven by reconnection events at the magnetopause. The second important frequency band ranges from 10 millihertz to our Nyquist (and above). This band contains a collection of coherent and incoherent oscillations. The coherent oscillations are short-lived packets which are believed to be generated in the upstream solar wind. The incoherent portion of the spectrum have been shown to be due to modulated electron beams impacting the ionosphere. Modulations of the beam intensity produce a quasi-periodic modification of the ionospheric conductivity and thereby quasi-periodic wavelets in the magnetometer record. Our analysis of the interstation coherence indicates that the beams have a coherence length of the order of 150 km. The work outlined above led to several published manuscripts, presentations and graduate theses.

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1. Introduction

During the early years of the 1990's the focus of the magnetospheric community turned to the dayside magnetosphere and to the interaction of the solar wind with the magnetopause. There, the transfer of mass, energy and momentum from the solar wind to the magnetosphere became important topics for study. During this period we were in a program of collaboration with colleagues in both hemispheres to study cusp phenomena and recognized an opportunity to contribute to this study. Our program of research has been a collaborative one since it is widely recognized that the complex magnetosphere-ionosphere interactions cannot be adequately measured with one instrument.

In the northern hemisphere, we began our study using the data from the Svalbard, Norway observatory at Longyearbyen. This observatory is unique among northern hemisphere sites in that it lies behind the terminator and beneath the cusp each day near noon for several months during the northern winter. Figure 1 shows the location of the site and the special geometry just described. This geometry allows optical and magnetic measurements to be made simultaneously. The Longyearbyen observatory is well instrumented with all-sky cameras, a meridian scanning and Fabry Perot photometers as well as with both fluxgate and induction magnetometers. In the southern hemisphere we collaborated with Dr. Brian Fraser who takes measurements at several sites in Antarctica which are nearly conjugate with the Longyearbyen site. Thus, with the support of the optical measurements to help understand the energy content of precipitating particles into the ionosphere we were able to begin our analysis of the cusp spectrum and the portions which showed conjugacy with the Australian sites.

Virtually all the analysis activity performed under this grant resulted in presentations, published manuscripts and theses. These are listed in section 4 below.

2. Instrumentation

We operated both induction and fluxgate magnetometers at the Longyearbyen site during the period of this study. Optical measurements obtained at the site were provided by colleagues at the Geophysical Institute. Conjugate measurements of the magnetic fluctuations near the cusp were provided by Dr. Fraser of the University of Newcastle, New South Wales, Australia.

The primary focus of our analysis is the data obtained from our induction magnetometer. The induction magnetometer is a simple instrument comprised of sensor coils, electronic amplifiers and filters and a computer-based data logger. The coils contain 10,000 turns of wire wrapped around a high-permeability core. Two coils are used at the Longyearbyen site to record the fluctuations in the horizontal components of the magnetic field. Signals

from the coils are amplified and filtered to prevent aliasing and then recorded directly to a tape unit. The signals from each coil are sampled every 10 seconds, giving a Nyquist frequency of 50 millihertz, and recorded to computer disk under the control of a data collecting program. Periodically, data are copied from the computer disk to tape and mailed back to the Geophysical Institute where they are archived and the data are incorporated into the geomagnetic data base.

Because the coils produce a voltage proportional to the time-rate of change of the local magnetic field, they are much more sensitive than ordinary fluxgate magnetometers to variations caused by ionospheric currents. The induction magnetometer used at Longyearbyen has an output voltage proportional to frequency over a frequency range from dc to approximately 2 hertz, the local resonance. The response decreases for frequencies higher than 2 hertz. When operated at frequencies below resonance the calibrations show a simple, linear proportionality between output voltage and input frequency with a constant given by: $V=5100Bf$. That is, a 1 nT sinusoidal variation with frequency of 1 millihertz would produce a 5.1 volt offset. Needless to say, the spectrum of fluctuations rarely exceeds rates of a few thousandths of a nT-Hz and output voltages are nominally in the 1 to 5 volt range. Similar instruments are operated by Dr. Fraser in Antarctica.

The all-sky camera at the Longyearbyen site is a "white light" camera, sensitive to all wavelengths and used primarily as a diagnostic of the auroral activity present during observations. The meridian-scanning photometer (MSP) at the Longyearbyen site is operated by members of the Geophysical Institute. It is comprised of a narrow beam photometer (angle of view: approximately 1 degree) which is mechanically rotated so that it scans the sky from southern horizon to northern horizon along the local geomagnetic meridian once every 16 seconds. The MSP gathers light in several important optical bands which can be used to infer the intensity and characteristic energy of the precipitating particles. Of special interest to our measurements near the cusp are the measurements at 630, 557.7 and 427.8 μm corresponding to the common red, green and blue auroral bands. Further details of this instrument can be found in Romick, 1976.

3. Analysis

The spectrum of magnetic fluctuations found near the cusp has been studied by several researchers. While reports of variations in several frequency bands were given in early studies, the earliest comprehensive study of the spectrum was given by Olson (1986). Other workers had identified important portions of the spectrum which provide the basis for segmenting the spectrum into areas for detailed study [Troitsakya, et al., 1985, Kato et al., 1985, Tonegawa et al. 1985, Engebretson et al., 1986, 1987]. Figure 2 contains a spectrogram showing the trace power recorded by the induction magnetometer at Longyearbyen on January 9, 1991. These data are typical of the events which are detected near the cusp. Evidence from the earlier investigations indicated that there were

two prominent, and physically different, regimes in the spectrum of cusp fluctuations. The first of these, termed Pc5, contains the lowest frequency variations ranging from dc to approximately 10 millihertz. The second, termed Pc3, contains variations ranging from just above 10 millihertz to well above our 50 millihertz Nyquist frequency. Clearly the division of the cusp spectrum into these bands is somewhat arbitrary since the spectrum appears to contain broadband fluctuations. However, the division separates regimes of differing physical sources and has become the accepted convention in the field.

A. The Low Frequencies: Pc5

As the observing site rotates under the ionospheric footprint of the magnetospheric cusp and boundary layers a sequence of characteristic variations are observed, some of which are conjugate. This sequence is also found to correlate with sequences of patterns in the optical MSP data. A few hours before local noon the level of fluctuations begins to increase and the time series is characterized by a sequence of individual pulses which show little coherence. These pulses appear to travel poleward and we have interpreted them as the signature of field aligned currents flowing into or out of the ionosphere. We assume these currents are produced by processes at the magnetopause, however at this time we are unable to distinguish between the currents produced by flux-transfer events and those produced by dynamic pressure changes at the magnetopause. Correlations with fluxgate magnetometer data as well as with optical data indicate these pulses are observed beneath the footprint of the magnetospheric boundary layers which lie just within the magnetopause.

Further rotation brings the station into the central cusp where the optical data show primarily 630 μm radiation and an absence of 557.7 and 427.8 μm indicating a very soft spectrum of precipitating electrons. Figure 3 shows the correlation between the MSP observations and the magnetic spectrum developed during this analysis. In this region the magnetometer signals appear to be short-lived packets of coherent variations. These packets show conjugate coherence and our analysis has produced evidence that they are driven oscillations of the last layer of closed field lines inside the magnetopause. Finally, as the station rotates into the afternoon sector the magnetometer signal is once again dominated by the poleward moving pulses characteristic of the footprint of the magnetopause boundary layers.

The analysis of this spectrum led to several presentations at national meetings, journal publications and a Ph.D. thesis listed in the summary of activity below.

B. The Intermediate Frequencies: Pc3

One of the most important group of signals associated with the cusp is contained within the Pc3 band between 10 millihertz and our Nyquist frequency of 50 millihertz. Signals in

this frequency band were recognized early as indicators of cusp proximity when observed on the ground. Analysis of the band showed the presence of two signal types. The first is comprised of short lived, coherent wave packets which are believed to be generated in the solar wind via the ion-cyclotron instability. Indeed their frequency has been shown to be proportional to the magnitude of the solar wind magnetic field. The second signal type is a broadband, quasi-periodic disturbance. Engebretson et al. (1990) showed these signals were of local (ionospheric) rather than distant (magnetospheric) origin. Using our conjugate stations we were able to show the coherent packets were sometimes seen at conjugate sites while the incoherent pulsations appeared to be local in nature, showing little coherence between hemispheres.

The broadband, incoherent Pc3 spectrum is presumed to be generated by electron beams precipitating into the ionosphere. Quasi-periodic modulations of the beam intensity is thought to produce variations in ionospheric conductivity, and thereby, in ionospheric current levels giving rise to the magnetic fluctuations observed at the ground. It occurred to us that we might obtain some indication of the spatial coherence of the beams by studying the spatial coherence of the magnetometer signals at the ground. We began the study by using data from Canadian cusp sites at Cape Parry and Sachs Harbor. In a preliminary analysis we were able to place an upper limit on the coherence length of the precipitating beams of approximately 200 km.

We have recently concluded a more extensive study using data from the extensive MACCS array operated through the NSF GEM program in northern Canada. With an array of sites at varying distances from each other we were able to obtain a model fit to the interstation coherences. Our result, shown in Figure 4, indicates that the interstation coherence diminishes with station separation, s , as: $C = \exp(-s/250)$. This result formed part of the Ph.D. thesis of C. Szuberla and will be presented at the fall 1997 AGU meeting. A manuscript is in preparation for publication.

A central fact which arises in the study of magnetospheric waves in the Pc3 band is that these pulsations are among the most ubiquitous variations present in the magnetosphere. There has been much conjecture as to the source of these variations focusing on the distinction between internal vs. external sources (see for instance Yumoto, K. 1986 for a review). We have made the suggestion that the cusp might be a source of magnetospheric Pc3. We had envisioned that the modulated currents which have been identified with the quasi-periodic variations detected near the cusp might radiate that energy back into the magnetosphere. A model study was performed as part of a Master's project by J. Williams who found that Pc3 energy from the cusp could radiate into the magnetosphere, but that it would be confined primarily to the outermost regions and not be a significant contributor to the wave field in the near-earth region.

4. Summary of Activity

Support from this grant was responsible, in part, for the following activity. The presentations, publications and theses represent the archived results of the research performed..

Presentations:

1995

- Olson, J.V. and C.A. Szuberla, Cusp Pc3 phase variations, *EOS*, **75**, 1994.
- Szuberla, C.A., M.G. McHarg, W.F. Denig, and J.V. Olson, Characteristic magnetic signatures of the cusp, *EOS*, **75**, 555, 1994.
- Williams, J.D. and J.V. Olson, A simulation study of Pc3-4 pulsations in the dayside magnetosphere with the cusp as a source, *EOS*, **75**, 555, 1994.
- Olson, J.V., C.A. Szuberla, B.J. Fraser and H. Hansen, A search for conjugate cusp Pc3, GEM Workshop, Snowmass, CO, June 1995.
- Ables, S.T., B.J. Fraser, J.V. Olson, H.J. Hansen, and F.W. Menk, Conjugate phase studies of Pc5 ULF field line resonances at cusp latitudes, GEM Workshop, Snowmass CO., June 1995.
- Ables, S.T., B.J. Fraser, J.V. Olson, H.J. Hansen and F.W. Menk, Conjugate ULF pulsations in the 1-10 mHz range at cusp latitudes, XXI IUGG Symposium GA3.06, Boulder, CO., July 1995.

1996

- Olson, J.V., A brief history of IPDP pulsations, *EOS*, **77**, s245, 1996.
- McHarg, M.G. and J.V. Olson, Ground based magnetometer measurements from Svalbard, Norway during the November 1993 storm, *EOS*, **77**, s227, 1996.
- Ables, S.T., B.J. Fraser, D.A. Neudegg, C.L. Waters and J.V. Olson, Interhemispheric phase studies of Pc5 pulsations, GEM Workshop, Snowmass CO, June 1996.
- Ables, S.T., B.J. Fraser, J.V. Olson, and D.A. Neudegg, Phase analysis of Pc5 pulsations recorded at cusp latitudes, AGU WPGM, Brisbane Australia, 1996.

1997

- Olson, J.V., C.A.L. Szuberla, M.J. Engebretson, B. Fraser and W.J. Hughes, Interstation Pc3 coherence at cusp latitudes, *EOS*, **78**, F595, 1997
- Szuberla, C.A. L., J.V. Olson, M.J. Engebretson, and W.J. Hughes, Spatiotemporal characteristics of cusp latitude spectra, *EOS*, **78**, F595, 1997
- Szuberla, C.A.L., J.V. Olson and B. Fraser, Pc3 coherence length at cusp latitudes, GEM Workshop, Snowmass CO, July 1997.

Publications

1995

McHarg, M.G., J.V. Olson and P. Newell, ULF cusp pulsations: Diurnal variations and interplanetary magnetic field correlations with ground based observations, *J. Geophys. Res.*, **100**, 19729, 1995.

1996

Kintner, P.M., J. Bonnell, R. Arnoldy, K. Lynch, C. Pollock, T. Moore, J. Holtet, C. Deehr, H. Stenbaek-Nielsen, R. Smith, J. Olson and J. Moen, The SCIFER experiment, *Geophys. Res. Lett.*, **23**, 1865, 1996.

Sun W., K. Shiokawa, K. Yumoto, T. Kitamura, J. Olson, and S.-I. Akasofu, The dependence of magnetic bays and the main phase of magnetic storms on latitude and magnetic local time, *J. Geophys. Res.*, 1996.

1997

Olson, J. V. and C. A. L. Szuberla, A study of Pc3 coherence at cusp latitudes, *J. Geophys. Res.*, **102**, 11375, 1997.

In preparation:

Szuberla, C.A. L., J.V. Olson, M.J. Engebretson, B.J. Fraser and W.J. Hughes, Interstation Pc3 coherence at cusp latitudes (to be submitted to *Geophys. Res. Lett.*)

Szuberla, C.A.L. and J.V. Olson, Spatiotemporal variations in cusp spectra (to be submitted to *J. Geophys. Res.*)

Theses

McHarg, M. G. , Ph.D. The Morphology and Electrodynamics of the Boreal Polar Winter Cusp, Physics Dept. University of Alaska, Fairbanks, September 1993.

Williams, J. M.S. Pc3-4 Propagation in the Dayside Magnetosphere, Physics Dept., University of Alaska, Fairbanks, May 1995

Szuberla, C. A. L. Ph.D. An Investigation of Cusp Latitude Magnetosphere-Ionosphere Physics: A Time Series Analysis Approach Physics Dept. University of Alaska, Fairbanks December 1997

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- Engebretson, M.J., L.J. Zanetti, T.A. Potemra, W. Baumjohann, H. Luhr, and M.H. Acuna, Simultaneous observation of Pc3-4 pulsations in the solar wind and in the earth's magnetosphere, *J. Geophys. Res.*, **92**, 10053, 1987.
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- Romick, G.J., The detection and study of the visible spectrum of the aurora and airglow, *Methods for Atm. Radiometry*, **91**, 63, 1976.
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- Troitskaya, V.A., ULF wave investigations in the dayside cusp, *Adv. Space Res.*, **5**(4), 219, 1985.
- Yumoto, K., Generation and propagation mechanisms of low-latitude magnetic pulsations – A review, *J. Geophys.*, **60**, 79, 1986.

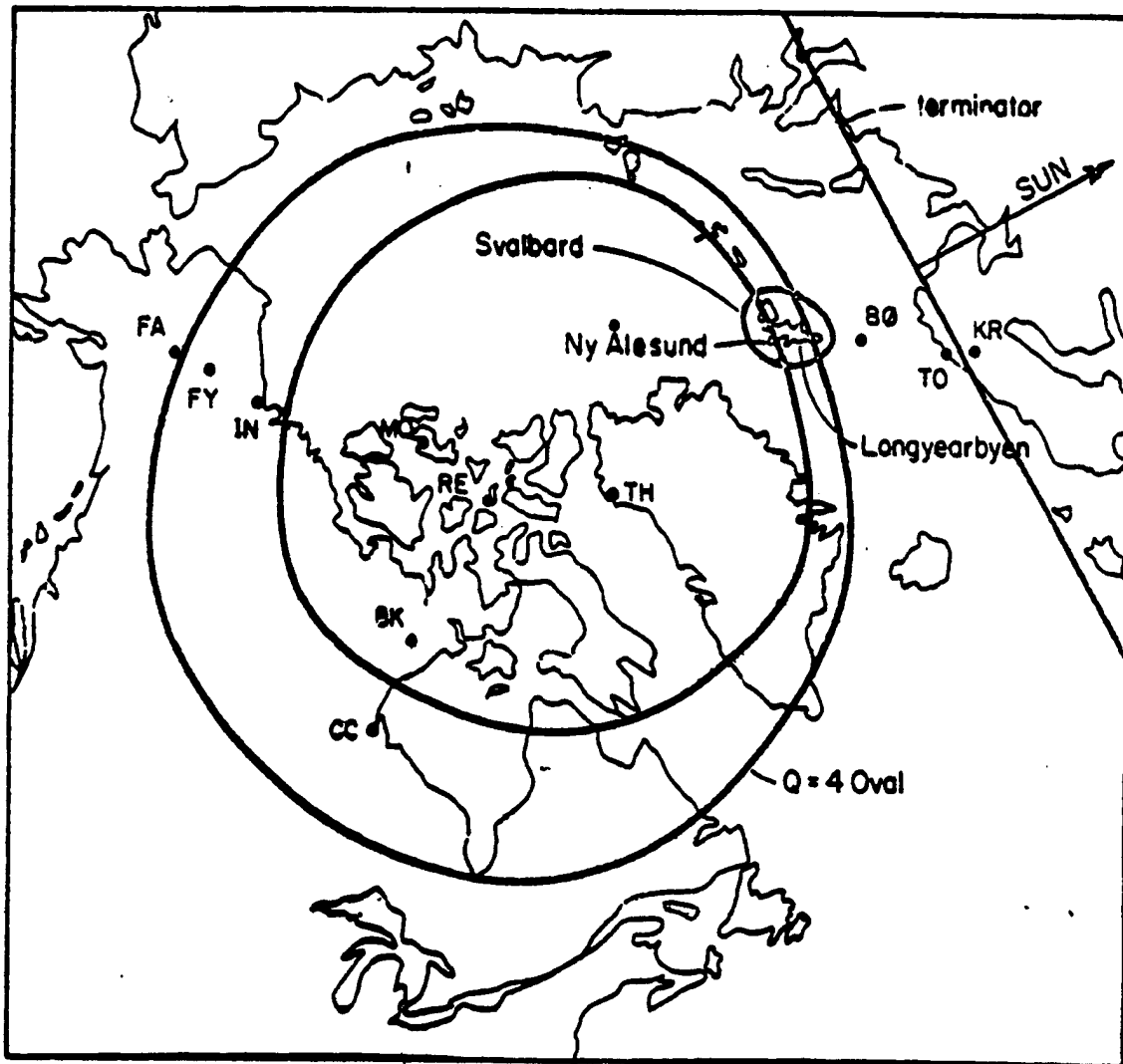


Figure 1. Polar view of the earth showing the auroral oval passing over Longyearbyen at noon local time placing the site below the cusp. Also shown is the terminator during northern winter. The darkened sky allows photometric measurements to be made of the ionospheric footprint of the dayside cusp.

Longyearbyen Induction Coils

9 Jan 1991

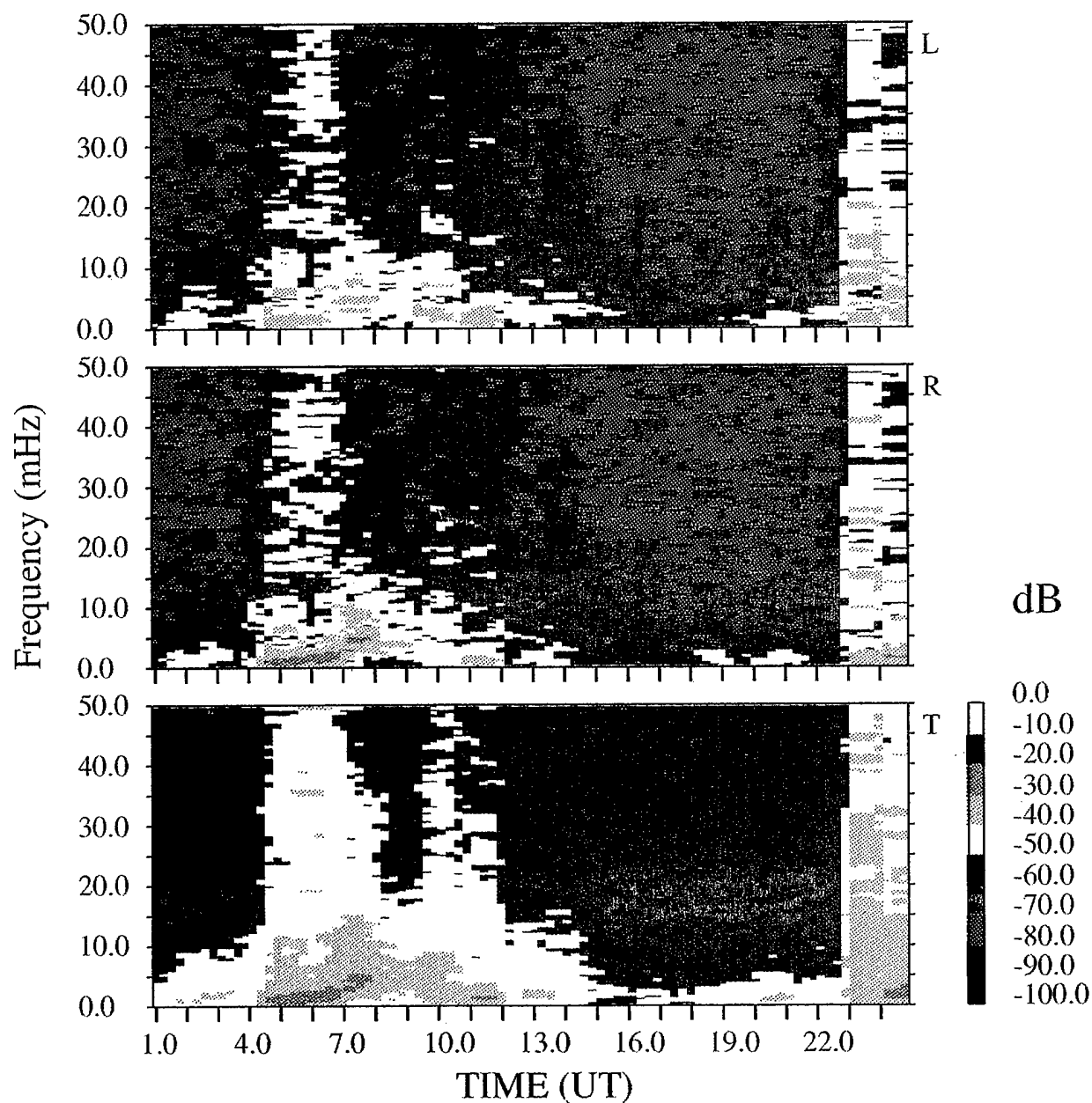


Figure 2. A spectrogram of ULF activity taken at Longyearbyen, 9 January 1991. Local noon is approximately 0900UT. Note that for several hours around local noon the spectrum shows enhanced power spanning the band from dc to 50 mhz. Also note that the signals between dc and 10 millihertz dominate the spectrum.

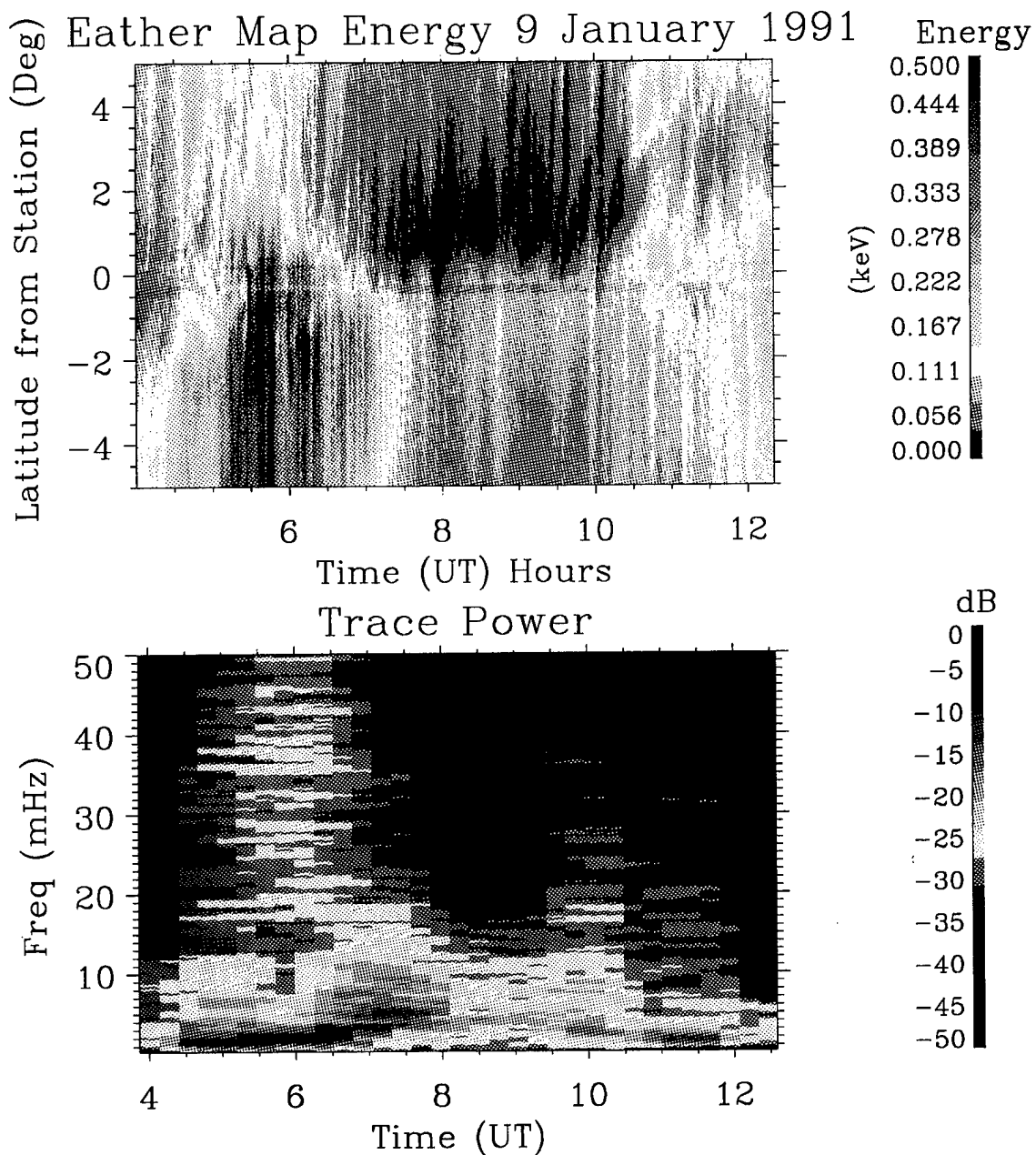


Figure 3. This figure shows the correlation between optical and magnetic measurements near the cusp. In the top panel we show a spectrogram of electron energies inferred from measurements with the meridian scanning photometer. The bottom panel is a spectrogram of the concurrent magnetic fluctuations. Note that near local noon (0900UT) the optical spectrum indicates low energy electrons (the cusp) while the bandwidth of the magnetic fluctuations is minimized. This correspondence allows the identification of the overhead cusp in the magnetometer records.

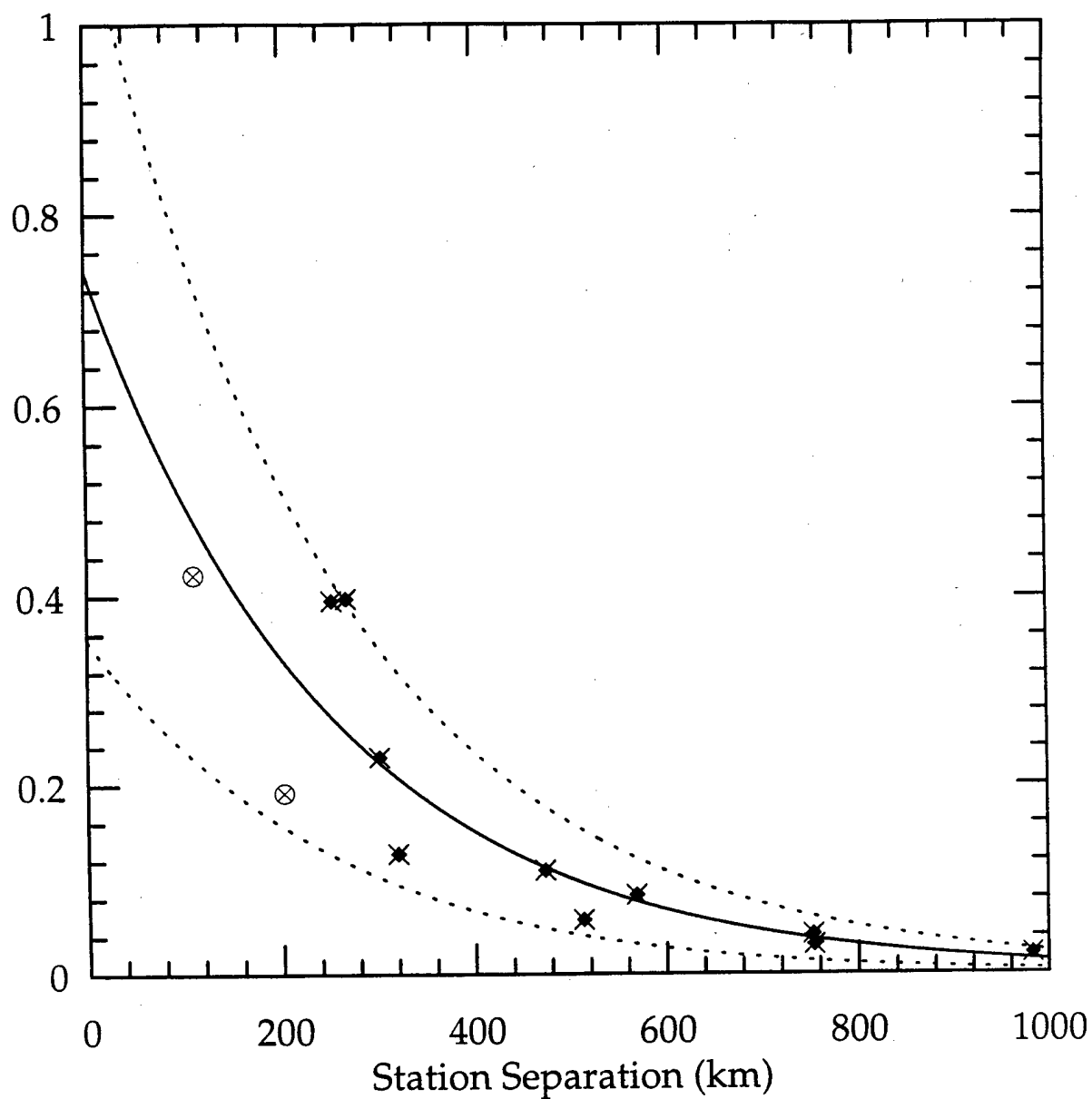


Figure 4. The inter-station correlation measured for the Pc3 band is plotted against station separation. Here we see that the correlation level diminishes with station separation. From these data we infer a coherence length of the precipitating electron beams to be of the order of 150 km.